7e Workshop International: Modelling Nutrient Digestion and Utilization in Farm Animals, 2009-09-10/2009-09-12, Paris, France.

A whole farm-model to simulate the environmental impacts of animal farming systems: MELODIE

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Abstract

Keywords:

Introduction

In regions of intensive pig and dairy farming, water quality can be threatened by nutrient losses from these farming systems. Greenhouse gases emissions from animal production contribute to climate change and ammonia emissions are a threat for air quality. Accumulation of trace elements like copper and zinc in soils are also sources of concern. But in mixed farms, manure and pasture can restore organic content of soils and improve soil structure and fertility. Although farming systems impact their environment in many different ways, positive or negative, nutrient flows are one of the first concerns, at least in regions of high animal densities. Nutrient flows and the subsequent impacts depend on many factors, including climate and soil type but also farmer decisions, from the strategic level (farming system: stocking rate, type of animal housing, crops grown, etc...) to the operational level (weather during waste application, etc...).

Changes of practices to improve one aspect can have negative consequences on other aspects, creating some dilemmas. An overall view of the system is required to avoid risks of pollution swapping. Therefore, environmental impact evaluations must include complementary criteria concerning the different aspects. Furthermore, decisions are mostly taken at farm scale. Because of the interactions between the different parts of the farm and the tradeoffs between different economic and/or environmental objectives, the environmental impact of a farming system may be different from what was inferred at lower scales. To be able to study these emerging properties, the choice was made to simulate nutrient flows at farm scale. However, at this scale, only emission indicators can be calculated, not impact indicators (Payraudeau and Van der Werf 2005).

Several dynamic models simulating farming systems exist. As far as pig and/or dairy farms are concerned, four dynamic mechanistic models deal with nutrient flows: the Integrated Farm Systems Model: IFSM (Rotz and Coiner 2004), DairyNZ’s Whole Farm Model: WFM (Wastney et al. 2002), Farm ASSEsment Tool: FASSET (Jacobsen et al. 1998) and DairyWise (Schils et al. 2007). IFSM and WFM are centred on the technical and economic results of the modelled farm and were not designed to perform long term simulations with decisions adapted to the context of each climatic year. FASSET uses a planning module generating a specific management at the beginning of each year, but little adaptations of the plan are made in the course of the year. DairyWise only performs simulations for an average climatic year. Thus, these models do not make it possible to study the interactions between climate variability, farm management and environmental impacts.

This paper presents the model MELODIE (french acronym for “object oriented model of animal farms to evaluate their environmental impacts”), which aims to evaluate ex ante the environmental impacts of production strategies in pig and dairy farms. The evaluation of the environmental impacts is centred on nutrient flows and the associated environmental risks. The model is intended to be used in research, to compare different strategies at different time scales. The aim is not to use it directly as a decision support system for farm management. MELODIE can be applied for the main systems encountered in France (where dairy and/or pig farm often also produce annual crops), and probably in many other countries thanks to its very flexible conception.

Model Description

Overview

MELODIE is a model simulating nutrient flows at the farm scale, in pig and dairy farms. The general organisation of the model is shown in figure 1. The nutrients taken into account are the ones whose losses are linked with environmental risks: carbon (C), nitrogen (N), phosphorus (P), potassium (K), copper (Cu) and zinc (Zn). Water (H2O) flows are also simulated. In order to take climate variability into account, long term (several decades) simulations are performed, which means that farmer decisions have to be modelled, at least for tactical and operational decisions. Integrating the effect of farmers' practices is a key element to find environmentally friendly production systems.

The main outputs of the model are the different products (crops, milk, meat) and the losses to the environment of different emissions, calculated daily over decades for each animal class, field or waste storage unit. These outputs can be used to calculate indicators of environmental impact, such as those used in Life Cycle Analysis (LCA).

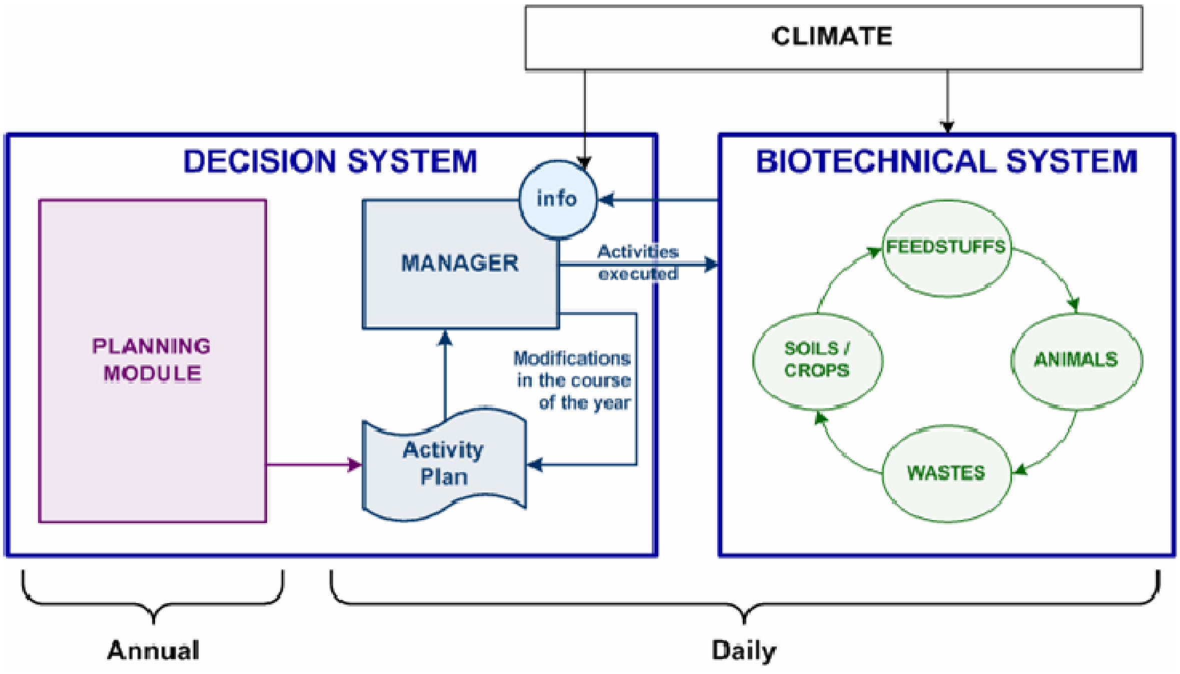

Figure 1 General organisation of MELODIE. The model consists of a biotechnical system interacting with a decision system.

MELODIE is based on the ontology of agricultural production systems (figure 2) proposed by Martin-Clouaire and Rellier (2003, 2009). In this ontology, a production system is composed of three subsystems: the biotechnical system (or controlled system), the decision system (or manager) and the operating system. The operating system includes the resources used to conduct activities, like labour and machinery. These resources are not taken into account in the present version of MELODIE, thus the operating system is not modelled.

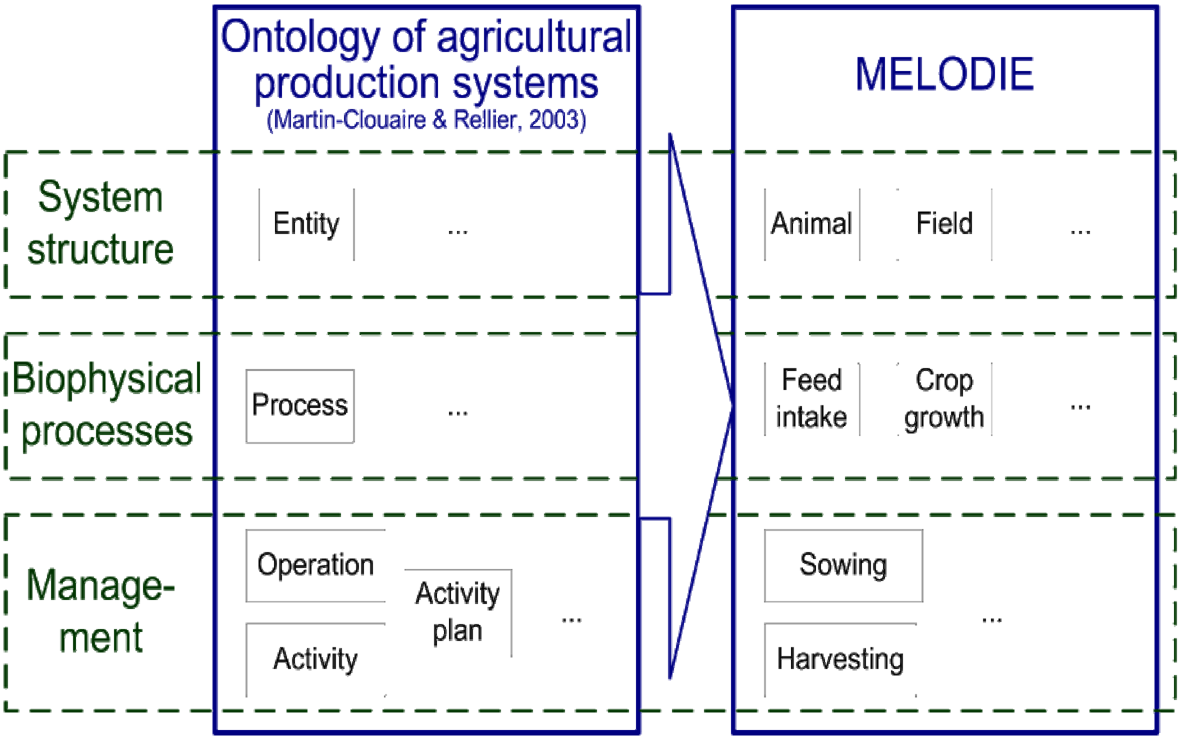

Figure 2 The objects of MELODIE are specialisations of broader concepts defined in an ontology of agricultural production systems

The biotechnical system

The nutrient flows are calculated at a daily time step by the biotechnical system, which is a set of connected sub-models. Four main nutrient pools are considered (fig. 1): animals, agricultural wastes (storage and treatment), soils and crops, and feed stocks. Nutrient losses to air and water are simulated, as well as nutrient flows between and within these pools. Different levels of precision are associated with the nutrients: for example, the N cycle is more detailed than the Cu or Zn flows, for which only balances between pools are calculated. MELODIE uses existing models wherever possible. For every process covered, the existing models or equations were studied, and the most appropriate were chosen. When no suitable model was found, new models were developed.

For soils and crops, each field is represented individually. MELODIE uses Stics (Brisson et al. 2003), a generic model simulating the flows of N, organic matter (i.e. C) and water, as well as crop growth and development. As far as P, K, Cu and Zn are concerned, mass balances at field scale are calculated, assuming average contents in crops. The nutrient contents of animal wastes are calculated within the wastes sub-model (see below).

Animals are not simulated individually, but by groups. For dairy cows and heifers, the model GEDEMO (Coquil et al. 2005) dynamically simulates the demography of the herd, i.e. the size of the 21 groups of homogeneous animals in terms of age and/or physiological status. For pigs, the demography model is based on practical references and expert knowledge, and is closely connected with the animal housing system. A group can be constituted either of sows managed together, or of fattening pigs born at the same cycle of a group of sows. For both pigs and cattle, the nutrient flows are calculated for each group, by multiplying an individual result, calculated for an average animal, by the size of the group. For dairy cattle, feed intakes are calculated using the equations of the INRA system (INRA 2007). The model of Maxin (2006) describes the nutrient (N, C, minerals, water) balances of dairy cattle and in particular allows calculating the nutrient content of urine and faeces as well as methane production, using easily available data. For pigs, the equations used for growth, feed intake and nutrient excretion of an individual are fully described in Rigolot (2009a).

The storage and treatment of all animal wastes are handled by a common module, which calculates the evolution of the wastes and the losses to the air, from the excretion to the land application. This module was built specifically for MELODIE from a set of existing empirical equations and emission factors (Rigolot 2009b).

The decision system

Decisions made by farmers are simulated by the decision system, which interacts with the biotechnical system throughout the simulation (figure 1). The role of the decision system is to dynamically determine the operations that should be applied to the different entities of the biotechnical system, in order to apply the farmer's management strategy. Decisions are taken at two time scales. Every year, a planning module generates plans. The ontology of agricultural production systems provides a consistent framework to describe explicitly these plans and their flexible application (and modification, if necessary and if an alternative strategy is available).

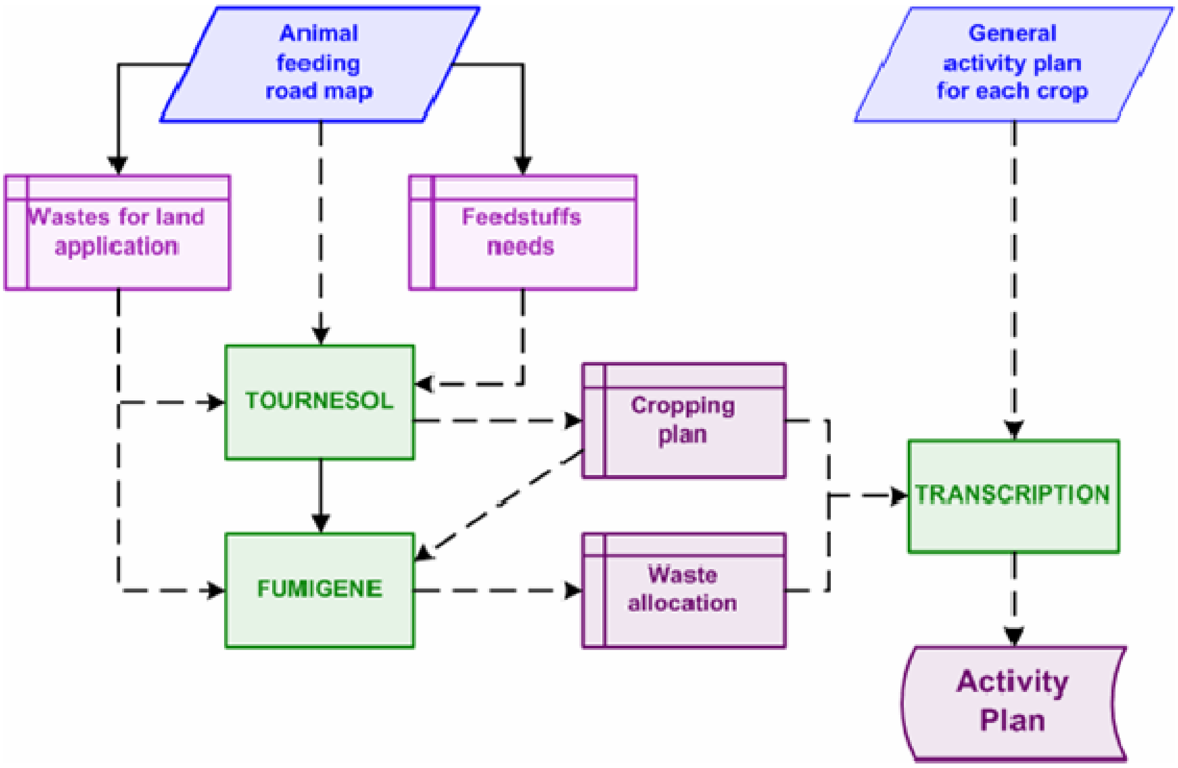

Figure 3 Organisation of the planning module, used to generate an activity plan for crops and waste management every year

The general organisation of the planning module is shown in figure 3. The goal of this module is to generate a cropping plan and a waste application plan for the upcoming year. Crops are allocated to fields by the cropping plan generator Tournesol (Garcia et al 2005). It considers the feed and straw requirements associated with the feeding strategy and applies agronomic knowledge (potential of the fields and effects of crop sequences) to generate a cropping plan that best satisfies the goals and priorities defined by the model user. Likewise, the model Fumigene (Chardon et al. 2007) is used to generate yearly waste allocation plans, according to the needs of each field and to management rules. The needs of each field are calculated using a balance sheet method which takes into account the type of soil, the history of the field (fertilisation and past cultivation of grass if any), the crop to be grown for the current year and its expected yield. The planning sub-models Tournesol and Fumigene interact with the biotechnical system by using information on the yearly variations of stocks of feed, straw and wastes. For example, if in a given year the quantity of grazed grass is high thanks to favourable conditions, the maize silage stocks will be high at the end of the year. The cropping area devoted to maize the following year will be decreased. Similarly, if the quantity of slurry is higher than expected, more slurry applications are planned. These interactions between planning sub models and the biotechnical system are a key feature of MELODIE, enabling the adaptation of practices to climate variability considered here on an interannual basis.

The activity plan is a set of activities organized by different temporal or programmatic operators that indicate how the plan should unfold (for example sequence or iteration). The plans are examined every day, for context-dependent application. The actual dates when activities should be executed are not included. The plan only contains time windows and “opening predicates” (conditions relating to the biophysical state) indicating when execution is possible. The operations scheduled are executed only when the conditions are suitable If necessary, the activity plan can be modified in the course of the events.

In MELODIE, these mechanisms are used, for example, to describe dairy cows feeding and in particular grazing management. Dairy cows feeding is adapted to the resources available on farm. It is thus very variable within years (several diets are used depending on the season) as well as between years (dates of transition between diets and quantities of complementary forage at grazing are variable).

The model user must provide a feeding road map for the animals, i.e. the feed (type and amount) to be provided, for different periods of the year and for different groups of animals (figure 4). The user must also provide an activity plan containing (i) the activities of transition between diets and (ii) the activities of grazing management (paddock changes and diet adjustment).

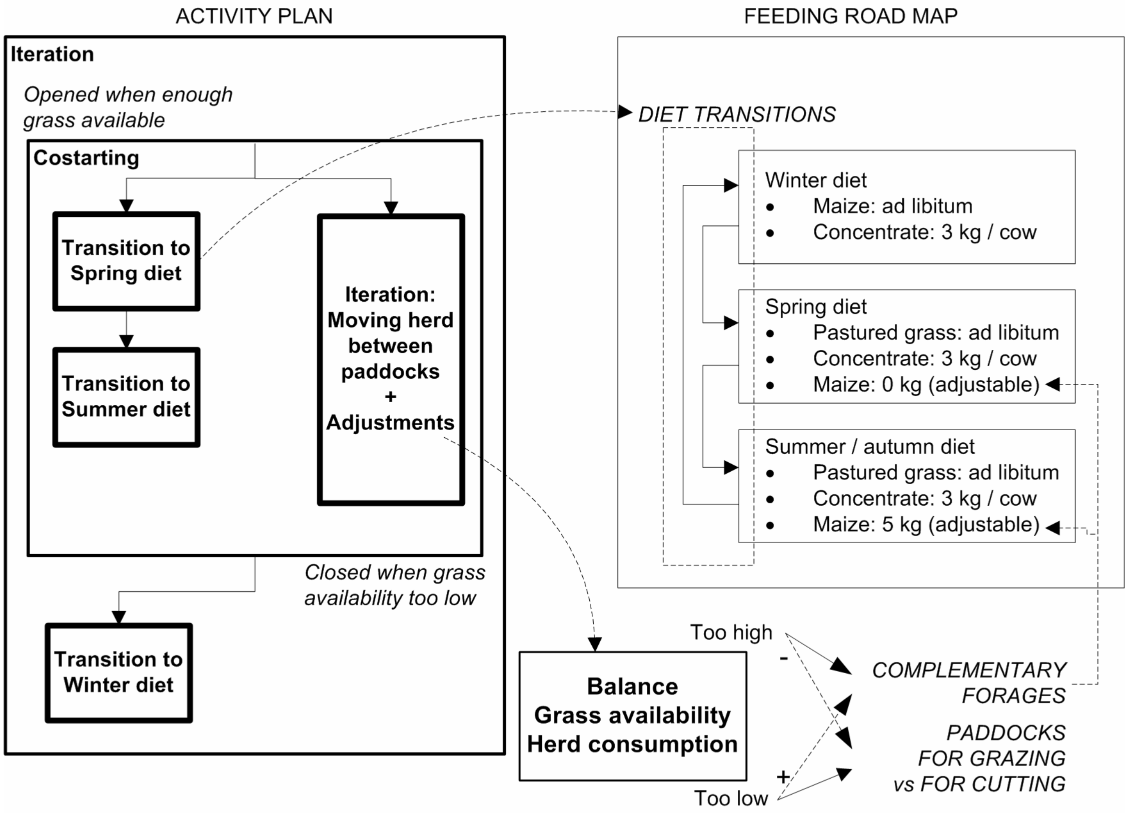

Figure 4 Example of feeding road map and activity plan for feeding. Flexible and dynamic management of feeding is defined by the combination of both.

At the beginning of a simulation, animals are indoors for wintering. In spring, when the quantity of grass available per cow on the whole farm reaches a fixed threshold, the opening predicate of the "turn out to grazing" activity becomes true, triggering the grazing season. During this period, an activity moving the herd from a paddock to another is iterated (figure 3). At each paddock change, the state of the system is examined and decisions are taken. The ratio between the quantity of grass available (total on all paddocks except those intended to be cut) and the quantity of grass eaten every day by the cows is compared to a desired interval (model input, in days). If too little grass is available, some paddocks initially intended to be cut are grazed and complementary forage is distributed. Conversely, if too much grass is available, complementary forage distribution is stopped and some paddocks can be cut as silage. The complementary forages to use are specified as an input of the model: each diet contains "adjustable" elements, which means that the quantities specified of the corresponding feed can be altered if necessary (figure 4). When not enough grass is available to feed the herd during one day after using "adjustable" elements, the herd goes back to its winter diet and stays indoors. It is possible to resume grazing during the same year when grass growth allows it. The whole mechanism described here is iterated throughout the simulations. The model user provides a single general description of the management with which long term simulations are performed, including adaptations to climate and grass growth variability. Animal feeding is therefore planned, but the plan leaves room for context-dependent application.

In summary, MELODIE includes models of the decision-making processes of farmers, which is relatively rare for models at this scale. The main strength of the decision system is the deep interactions with the biotechnical system, in the operational management during the year as well as in the planning step taken every year. Thanks to these interactions at two time steps, farm management is permanently adjusted to climate conditions and to the state of the system, which is a key feature for realistic simulations of farming systems on the long term and to study both the management variability and the resilience of farming systems.

Discussion

Consistency of the farming systems simulated

MELODIE was designed to perform ex ante evaluations of farming systems. The goal is to evaluate different systems, existing or not, in the same context. A major difficulty is to ensure the consistency of the system simulated, particularly for those which do not yet exist in commercial farms. For example, the cropping plan must match the feeding road map of the animals and the level of feed autonomy targeted by the farmer. In Melodie, the planning module plays a key role in this regard, because it ensures the consistency of the different elements of the plan. To design a new system, it is necessary to provide the animal feeding road map, and the farmer's goals and priorities used by Tournesol and Fumigene. The cropping plan and the waste management plan are then automatically generated each year, so as to best match the goals defined by the model user. The consistency of the generated system depends on the consistency of the goals and their representation.

Another element of consistency in ex ante evaluation is the capability of the decision-making process to cope with climate variability and to respond to the state of the biophysical system. In practise, management decisions can vary greatly between years, in terms of dates and parameters of the activities planned, and even in terms of activities executed. The plans must be flexible and leave room for context-dependent adaptation. In MELODIE, climate variability is taken into account at two levels, thanks to the interactions between the decision system and the biotechnical system. On a yearly basis, the planning module integrates the variations of the stocks of feed and animal wastes. In the course of the year, farm management can also be very variable depending on the conditions, as demonstrated earlier in the case of herd feeding. In the model, the management is thus automatically consistent with the state of the system, provided that the decision system is correctly modelled.

The decision system in MELODIE also makes the management spatially consistent. Decisions are taken according to factors specific of each field. Two fields with the same crop can be managed differently, particularly in terms of fertilisation. During a long term simulation, each field follows its own trajectory, and the consistency is enforced at the whole farm scale. Spatial heterogeneity creates constraints and opportunities which justify taking decisions for each field individually. This capacity of the model could be particularly efficient to upscale farm models to a territory with a true spatial dimension.

Model applications

MELODIE is intended to be used in research and development, to compare the environmental impact of different production strategies in several series of yearly climatic scenarios. MELODIE is not intended to be used directly on farm as a decision support system, but should be considered as a virtual experimentation framework. The simulations should be designed like real experiments would be. Simulations can be performed for typical farm configurations in a region, in order to propose the most desirable practises and evolution in each case. MELODIE is complementary with other methods of investigation.

Conclusion

As a conclusion, MELODIE is a true whole farm model made possible by the association of biotechnical and decision models. It upscales a set of pre-existing models of animal, plant-soil and biological processes in effluents and new decision models which are combined in a generic structure relying on the object-oriented paradigm. Thanks to this change of level of organisation, MELODIE is a framework for virtual experimentation on animal systems. It enables users to perform multi-criteria ex ante evaluations of the environmental pressures resulting from production strategies. Such evaluations are complementary with experimental approaches and MELODIE can be extended to include new knowledge on nutrient flows and the underlying biophysical processes. MELODIE could also be extended to deal with other issues than nutrient flows, for example in order to provide evaluations of sustainability.